

Increasing the Service Life of Bridge Decks by Incorporating Phase Change Materials (PCMs) to Reduce Freeze/Thaw Cycles

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Abstract

During a freezing event, pore solution in cementitious bodies expands and creates stresses that can cause damage; therefore, reducing the number of freeze/thaw cycles experienced by a structure will extend the structure's service life. The incorporation of phase change materials (PCMs) as a way to reduce the number of freeze/thaw cycles experienced by bridge decks has been investigated by modeling and mechanical testing, calorimetry, and x-ray microtomography. Models identified regions where freeze/thaw damage is not a significant concern, as well as regions where this technology may be practical, increasing the service life of a bridge deck by at least one year. The incorporation of PCM reduces strength by varying amounts, and for varying reasons, depending on which PCM is used and how it is introduced into the concrete. As a variety of methods exist to address this loss in strength, PCM incorporation is a promising technique for addressing one aspect of the impending infrastructure crisis in the United States.

1 – Introduction

Although bridges account for roughly 40 % of national infrastructure maintenance costs (about \$10 billion annually), in 2009 the American Society of Civil Engineers (ASCE) issued an overall grade of ‘C’, or ‘mediocre’, to the nation’s bridges [1, 2]. That same year, the American Association of State Highway and Transportation Officers (AASHTO) listed ‘age and deterioration’ first on a list of the ‘top five problems for bridges’ [3]. Over 150,000 bridges (roughly one in four) are either structurally deficient or functionally obsolete [4]. At an average price of \$50/square foot, replacing the bridge decks of all structurally deficient or functionally obsolete bridges in the United States would cost nearly \$49 billion, though the ASCE estimates that an annual \$7 billion increase in funding every year would be required to “substantially improve bridge conditions” [4-6]. As infrastructure continues to age, the amount of money needed for maintenance is expected to rapidly increase: the average American bridge was constructed in 1966 and expected to last for 50 years [3]. Unless the nation is to face a similar crisis in the future, new technologies that extend the service life of bridge decks are needed.

One of the most important factors affecting the service life of a bridge deck is the corrosion of reinforcing steel [7]. Exposure to freeze/thaw cycles can accelerate corrosion, as solutions in the pores of concrete expand during a freezing event and exert pressures that lead to the creation of cracks. These cracks provide aggressive media such as de-icing salts easy access to reinforcing steel [8]. The presence of water in cracks then further increases the amount of deterioration caused by successive freeze/thaw cycles. Although cracking can be caused by a variety of other mechanisms, and a variety of techniques have been developed to prevent or mitigate the effects of cracking, freeze/thaw damage still plays a significant role in limiting bridge deck service life [7].

The number of freeze/thaw cycles experienced by a bridge deck can be reduced by incorporating phase change materials (PCMs), materials with high enthalpies of phase change (ΔH) [9-11]. At a given temperature (T_{MELT}) PCMs solidify, releasing energy and maintaining surrounding temperatures at T_{MELT} . If enough energy can be released in this way (dictated by ΔH) a freezing event, and the associated damage, can be prevented [12, 13].

PCM can easily be introduced into a system by a variety of methods, most commonly as macro- or micro-encapsulated ‘pellets’ [14, 15]. These pellets are, essentially, polymer spheres containing PCM and an appropriate amount of empty space for the accommodation of volumetric changes with temperature. Alternatively, lightweight aggregate (LWA) can be used; LWA is a porous aggregate that can absorb and hold liquids by capillary action [16]. These aggregates are commonly used for internal curing (supplying additional water to the cement paste so as to encourage more complete hydration), and are graded in such a manner that fine aggregate (i.e. sand) can simply be replaced by similarly sized LWA during mix design.

This study investigates the use of PCM as a means by which to increase bridge deck durability by reducing freeze/thaw cycling. The effects of 12 different PCMs in 237 different locations were modeled using a combination of the CONCTEMP program developed at the National Institute of Standards and Technology (NIST) and a service life prediction model developed for the Indiana Department of Transportation (INDOT). Mortars containing PCM were produced to investigate the effects of PCM incorporation on mechanical properties, on the rate of hydration, and to investigate the 3D microstructure with x-ray microtomography.

2 – Methodology

2.1 – Experimental

Four mortars were investigated: a control, a mix containing a paraffin wax (PCM6) in LWA, a mix containing a vegetable oil (PT4) in LWA, and a formula containing PT4 encapsulated in polymer. The composition of each formula can be found in Table 1. The cement used was a commercially available ASTM C150 Type II cement. The aggregate was a mixture of four different normal-weight sands which has previously been used in studies involving LWA [17]. The LWA used was a commercially available expanded clay corresponding to standard ASTM C330, “Specification for Lightweight Aggregate for Structural Concrete”. The mass ratio of water:cement was fixed at 0.35; the volume fraction of sand was 55 %. Tap water was used throughout.

The quantity of LWA used was based on the LWA’s previously determined maximum absorption of 26.5 % by mass [17]. LWA was incorporated into the formulae simply by replacing normal-weight sand, ensuring that the gradation of aggregate particle sizes in all mortars was the same. Theoretically, the amount of LWA used could absorb up to 22 g more liquid than the amount of PCM used. Therefore, in the two mixes containing LWA-PCM, an additional 30 g of mix water was used to ensure that the LWA did not dehydrate the system. The LWA was saturated with PCM by immersion and agitation on a shaker-mixer for 1 hour. The amount of encapsulated PCM to be used was calculated with the knowledge that each pellet contains the mass ratio of PCM to encapsulation media of 4:1.

Mortar preparation was performed in accordance with ASTM C109 with the exception that, when used, the PCM (in either LWA-PCM or encapsulated form) was added immediately after the aggregate. Specimens were placed in steel molds in plastic bags, placed in an environmental chamber, removed from the molds after 24 hours, and submerged in water in a temperature-controlled cabinet. Compression tests were performed at 3 d, 7 d, and 28 d on no fewer than 5 specimens.

One cube specimen of each mortar was placed in a sealed plastic bag after failure in the compression test. The specimen was sawn into three equal sections using oil as the cutting lubricant, wiped dry, and placed in a plastic bag. The two outer sections of the specimen were used to determine thermal properties using Transient Plane Source (TPS) analysis, which has been described in [18, 19]. A 6.403 mm radius probe (Ni foil encased in Kapton) was sandwiched between two faces of the specimen (to minimize possible artifacts caused during the sawing, the outer surface faces were used in every experiment). Measurements were taken every 45 minutes after an equilibration time of 45 minutes. Five measurements of thermal conductivity and volumetric heat capacity were recorded. Measurements were taken at either 22 °C or 23 °C with a power of 0.3 W applied over 10 s. The volumetric heat capacity, provided by the system, was then converted to specific heat capacity (mass basis) by dividing by average density (calculated by weighing and measuring cubes before compression tests). According to the manufacturer, thermal conductivity measurements on homogeneous materials are reproducible within $\pm 2\%$, while heat capacity is reproducible within $\pm 7\%$. After the dry measurements were made, sections were placed in a limewater bath for 7 days. The sections were removed, patted dry, and re-measured, with the entire apparatus placed inside a plastic bag to minimize drying over time.

The middle section of the specimen was further sawn down to produce a small sample for analysis by x-ray microtomography. These tests were performed at a voltage of 200 kV and a

tube current of 200 μA , at an output resolution of 4000 pixels x 2096 pixels, a spatial resolution of about 5 $\mu\text{m}/\text{pixel}$, scanned at 0.3° per step, 5 frames averaged, and a full 360 degree rotation.

2.2 – Modeling

Bridge deck modeling was performed using the CONCTEMP program developed at NIST [20]. The model predicts time-of-wetness (due to both precipitation and condensation), surface temperature, and time-of-freezing for bridge decks based on a one-dimensional finite difference scheme that includes heat transfer by convection, conduction, and radiation. Radiation considers both solar radiation as a source and radiative cooling to the sky (greater at night) as a sink. A full description of CONCTEMP can be found in [20].

CONCTEMP requires the user to define several variables, including thermal and physical properties of both the concrete and PCM. The values for the concrete (heat capacity, thermal conductivity, and density) were set at 1000 J/kg·K, 1.5 W/m·K, and 2350 kg/m³, respectively. The latter two values are particularly conservative (see below). Of the 12 different PCMs investigated, two (PT4 and PCM6) are commercially available products¹ for which ΔH and T_{MELT} were supplied by the manufacturer. ΔH and T_{MELT} values used for the other 10 PCMs were based on a recent review by Cabeza *et al.* [9] (Table 2). Where a range was reported for a value, a simple average was used here. The 12 PCMs represent a relatively broad range of both ΔH (153 J/g to 295 J/g), and T_{MELT} (0 °C to 8 °C). The final user-defined variable is the PCM concentration in the concrete, set at 0 kg/m³ (control bridge deck), 50 kg/m³ (practical PCM loading), or 120 kg/m³ (estimated maximum possible PCM loading).

Typical Meteorological Year 2 (TMY2) datasets, produced by the Analytic Studies Division of the National Renewable Energy Laboratory [21], provided the program with data relating to weather factors for the area in which the bridge deck is located (specifically: time, ambient and dewpoint temperatures, relative humidity, wind speed, precipitation levels, incident global horizontal solar radiation, and percentage of cloud cover). TMY2 datasets are hourly values of various weather factors that would be experienced over a ‘typical year’ for a given location, determined statistically from weather recorded between 1961 and 1990. 237 locations for which TMY2 data exist (covering 46 states, 4 commonwealths, and the unincorporated organized territories of Guam and the Commonwealth of Puerto Rico) were investigated.

To estimate bridge deck service life, a model developed by Barde *et al.* for the Indiana Department of Transportation (INDOT) was used, which is briefly reviewed here and detailed in [22]. This model considers two factors: $\text{LIFE}_{\text{INITIAL}}$, the length of time required for a bridge deck to reach a critical saturation (after which damage will begin to accumulate), and $\text{LIFE}_{\text{SECONDARY}}$, the length of time required for a bridge deck to reach a user-defined level of damage.

$\text{LIFE}_{\text{INITIAL}}$ is approximated using the time required to reach a critical saturation value (t_w , the numerator of eq. 1) as well as the cumulative length of wetness events lasting longer than the nick-point time [23]:

$$\text{LIFE}_{\text{INITIAL}} = \frac{t_w}{t_{w/\text{nickpt}}} = \frac{\left[\frac{S_{CR} - S_b}{(V_P + V_{AIR})D} \right]}{t_{w/\text{nickpt}}} \quad (1)$$

¹ Certain commercial equipment, instruments, or materials are identified in this report in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

where t_w is a function of the percentages of entrained air (V_{AIR}) and porosity (V_P), bridge deck depth (D), critical saturation level (S_{CR}), and the saturation at the nick-point time (S_b).

The nick-point time represents the time at which the sorptivity of the concrete changes from initial sorptivity to secondary sorptivity [23]. During initial sorptivity, only capillary and gel pores fill with solution. The volumetric expansion of this solution as it freezes can be accommodated by the air void system; thus no damage occurs during freeze/thaw cycling. The cumulative length of wetness events lasting longer than the nick-point time ($t_{w/nickpoint}$) is essentially a measure of how much water the air void system has been exposed to or how ‘full’ the air void system is. The nick-point time was set at 6 hours; because the TMY2 datasets do not report fractions, the cumulative length of wetting events longer than the nick-point time was calculated including wetting events that lasted *exactly* 6 hours, rather than *more than* 6 hours.

During secondary sorptivity, the air void system itself begins to fill with solution, can no longer accommodate the volumetric expansion of solution during freezing, and damage will occur during a freeze/thaw cycle. Saturation at the nick-point time (S_b) is calculated using an additional fitting factor, b , equaling 5.5 mm, and an initial saturation value, $S_{INITIAL}$:

$$S_b = S_{INITIAL} + \frac{S_{INITIAL}\sqrt{t_{nickpt}} + b}{(V_P + V_{AIR})D} \quad (2)$$

$S_{INITIAL}$ can be estimated for concrete in a given location based on absorption isotherms and the relative humidity (RH) immediately preceding a wetting event (RH is supplied in the TMY2 datasets). Because the 237 locations investigated here have roughly similar values of RH before a wetting event ($84 \pm 6.6\%$), and because a range of absorption isotherms have been published, a single estimated value for $S_{INITIAL}$ of 0.56 was used for all locations, rather than re-estimating initial saturation at each location. The method used to estimate $S_{INITIAL}$, as well as the absorption isotherms, can be found in [22].

The second factor in service life, $LIFE_{SECONDARY}$, is a measure of the length of time required for the properties of the concrete (compressive/flexural/tensile strength, resonant frequency, etc.) to fall to a user-defined damage level (D_S):

$$LIFE_{SECONDARY} = \left[\frac{D_S}{A \Delta S} \right] \frac{1}{n} \quad (3)$$

where A and ΔS are constants unique to each concrete, and n is the number of freeze/thaw cycles experienced by the structure in a ‘typical’ year (provided by the TMY2 datasets).

Total service life is simply the sum of $LIFE_{INITIAL}$ and $LIFE_{SECONDARY}$:

$$TOTAL \ SERVICE \ LIFE = \left[\frac{\left[\frac{S_{CR} - S_B}{(V_P + V_{AIR})D} \right]^2}{t_{w-nickpt}} \right] + \left[\frac{D_S}{A \Delta S} \right] \frac{1}{n} \quad (4)$$

The user-defined values used here (Table 3) are generally the same as those selected by Barde et al. [22].

3 – Results and Discussion

Four mortars were produced for physical and thermal characterization: a control formula, and formulae containing PT4 in LWA, PCM6 in LWA, or microencapsulated PT4. If the incorporation of PCM has a significant effect on physical properties such as strength, heat evolution, and thermal conductivity, the system will not be viable, regardless of the modeling results.

3.1 – Compressive Strength

When compared to the control mortar, the three mortars containing PCM attained lower compressive strengths at all ages (Fig. 1). After three days, the control mortar reached a compressive strength of 49.1 ± 1.9 MPa (7116 ± 281 psi); the incorporation of PT4 in LWA, PCM6 in LWA, and microencapsulated PT4 reduced compressive strength by 38 %, 18 %, and 15 %, respectively. At 7 days, the control mortar reached a compressive strength of 55.8 ± 1.7 MPa (8093 ± 241 psi), and the three encapsulation methods reduced strength 39 %, 16 %, and 20 %, respectively. Finally, at 28 days, the control mortar reached a compressive strength of 60.3 ± 3.1 MPa (8754 ± 462 psi), and was reduced by 29 %, 8 %, and 18 %, by the three encapsulation methods, respectively.

In the mortar containing encapsulated PT4, the lower compressive strength observed is likely due to mechanical reasons, as the capsules are relatively weak and encourage the nucleation of cracks. This effect will likely be a function of the size of the PCM capsules employed, and it is unlikely that the current product has been optimized for such utilization in mortars and concretes. For the two mortars containing PCM in LWA, the reduced compressive strengths are likely due to a combination of several factors:

- If the LWA exchanges PCM with water from the cementitious matrix, it may dehydrate the system, resulting in a lower degree of hydration;
- If the LWA releases PCM into the cementitious matrix, the PCM could act as a retardant by coating cement particles, hampering the transport of water into those particles and thus reducing the rate and degree of hydration; and,
- The LWA is simply a weaker aggregate than sand, due partially to the fact that LWA is rather porous.

It is possible that simply adding an additional dose of LWA soaked in water, to act as internal curing agent, will counteract system dehydration. The only way to counteract the retardant effects of PCM is to ensure that either a) the LWA does not release any of the PCM, or b) a PCM is used that does not have a retardant effect on cement hydration. The effects of LWA being a weaker aggregate can only be addressed by either finding a different LWA or a different incorporation method. What portion of the reduction in strength is due to which mechanism is not entirely clear, however, and requires further study. Strength reductions of 20 % or less might be offset by a reduction in the water to cement ratio, for example.

3.2 – Isothermal Calorimetry

In light of the strength results, isothermal calorimetry was used to quantify heat evolution, which is directly related to hydration reactions in cement. The two mortars containing LWA-PCM and the control mortar were investigated; the more heterogeneous nature of the encapsulated PCM made analysis difficult.

The results indicate that the lowered compressive strengths are due to two distinct mechanisms (Fig. 2). The heat evolution curves of the control and the formula containing PCM6 are almost identical; this indicates that hydration was not retarded or reduced by the presence of PCM6, either because the LWA does not release PCM or, if released, the PCM does not act as a retardant. The reduced strength, therefore, is likely due to a purely mechanical reason, that is, the weakness of the LWA as an aggregate. This conclusion is supported by the observation that, at any age, the strength of the formula containing PCM6 is similar to the strength of the formula containing microencapsulated PT4, where the reduced strength is clearly an effect of adding the relatively weak polymer pellets.

The heat evolution curve of the mortar containing PT4 is quite distinct from that of the control mortar. Heat evolution is not only delayed, but the maximum heat flow is reduced. This indicates that the incorporation of PT4 is having a significant effect on hydration, either because the PCM is acting as a retardant or because the LWA is dehydrating the system. It is likely that both are occurring, as the first mechanism encourages the second.

3.3 – Thermal Conductivity and Heat Capacity

Stoll *et al.* reported that the incorporation of PCM in concretes lowered the thermal conductivity of the system, negatively affecting overall performance by reducing heat transfer from the core to the surface, and from solar energy to the core to ‘recharge’ the PCM [14]. Reduced thermal conductivity was identified as a possible substantial practical hurdle.

In dry conditions, the mortars incorporating PT4 in LWA, PCM6 in LWA, and encapsulated PT4 had thermal conductivities of 51 %, 61 %, and 93 %, respectively, of that of the control mortar (2.67 ± 0.041 W/m·K, Table 4). The presence of water in saturated surface dry conditions, which are more representative of the conditions under which freeze/thaw damage will occur, increased the thermal conductivity of all mixes by roughly 0.3 W/m·K (i.e. 10 %), but the same general trend was evident: the thermal conductivities of PT4 in LWA, PCM6 in LWA, and encapsulated PT4 were 61 %, 69 %, and 92 % of the control mix (2.935 ± 0.739 W/m·K).

Specific heat, which was simultaneously measured, showed no apparent trend: the three mortars, respectively, had specific heats that were 101 %, 75 %, and 140 % that of the control mortar in dry conditions. When saturated, the three respective mortars had specific heats of 107 %, 103 %, and 136 % that of the control mix, suggesting a higher specific heat for the encapsulated PCM itself.

3.4 – X-Ray Microtomography

Several phases were easily discernible in x-ray microtomographs, including (in order of increasing density, and thus brightness): pores, encapsulated PCM pellets, LWA, quartz aggregate, and cement paste matrix (Fig. 3). The pores and encapsulated PCM have similar brightnesses but can be distinguished by size. The diameter of an encapsulated PCM pellet is on the order of 3 mm, while the largest pores identified were well below the millimeter scale. LWA and quartz aggregate were generally similar in size and shape, although the size distribution of the LWA tends towards slightly larger particles. The LWA is also substantially darker in x-ray microtomographs. Unfortunately, the densities of dry LWA, LWA with absorbed PCM, and LWA with absorbed water are similar enough that the three cannot be easily differentiated based on brightness (assuming that all three phases were present in the sample). X-ray microtomography has, however, been previously used to identify the movement of water from

LWA to the cement paste [17]; since the LWA and the quartz aggregate are distinct from each other, this technique may be useful in future studies of the rate at which LWA releases PCM.

3.5 – Modeling

3.5.1 – Determination of Practical Locations

In general, the 237 locations investigated can be split into two groups: locations where freeze/thaw damage significantly affects the service life of a bridge deck, and locations where it does not. Freeze/thaw damage may not significantly affect the service life of a bridge deck either because the area is too dry (i.e. $LIFE_{INITIAL}$ is relatively high) or because the area is too warm (i.e. $LIFE_{SECONDARY}$ is relatively high). Locations where freeze/thaw damage does have a significant effect on service life can be further broken into two categories: locations where the incorporation of PCM is likely to be practical, and those where it is not (Fig. 4).

Lopez-Anido, in a survey of data from various departments of transportation, found that bridge decks in ‘moderate climate regions,’ where the main deterioration mechanism is unrelated to freeze/thaw damage, require initial maintenance after an average of 20 years [6]. This value was chosen as an upper limit: if either $LIFE_{INITIAL}$ or $LIFE_{SECONDARY}$ are greater than 20 years, reducing freeze/thaw cycles through the incorporation of PCMs is not necessary because freeze/thaw damage is not likely to be a predominant deterioration mechanism. A total of 41 locations receive so little precipitation that $LIFE_{INITIAL}$ was calculated to be greater than 20 years (Fig. 5a). These locations are predominantly in the ‘Mountain West’ states stretching from North Dakota to Arizona. A further 21 locations experienced so few freezing events that $LIFE_{SECONDARY}$ was calculated to be greater than 20 years (Fig. 5a); these are generally limited to points along the gulf coast, California, and all points in Hawaii, Guam, and Puerto Rico.

Although incorporation of PCM should increase the service life of a bridge deck in the remaining 175 locations, the increase in service life is not necessarily significant. One year was selected to separate significant and insignificant increases, partially because construction is a seasonal activity: extending a bridge deck service life by a few months, necessitating replacement in winter instead of summer, is not practical. In 125 of the remaining locations (generally in Alaska, the Midwest, and New England) none of the 12 PCMs investigated were able to increase service life by at least 1 year at a PCM loading of 50 kg/m^3 (Fig. 5b).

The final 50 locations meet two criteria: freeze/thaw cycles are likely to significantly influence the lifespan of a bridge deck, and at least one of the 12 PCMs investigated increased the estimated service life of a bridge deck by at least one year at a PCM loading of 50 kg/m^3 . These 50 (Table 5, Fig. 5b) locations are found in a band across the southeast (south of the line Richmond-Knoxville-Oklahoma City, but north of the line Tallahassee-Mobile-San Antonio) and along the northwest coast (west of the line Fresno-Eugene-Seattle).

While 50 kg/m^3 (roughly 2 % by mass) is a feasible, conservative estimate, based on the absorptive properties and particle size gradation of the LWA used here, roughly 120 kg/m^3 is the maximum amount of PCM that could be incorporated by simply substituting LWA for regular aggregate. When CONCTEMP was run using this maximum concentration, an additional 41 locations were identified where service life would be increased by at least one year (Fig. 5c). The minority of these locations are in Alaska and the Pacific Northwest, while the majority are north of the previously identified band across the southeast. At a PCM density of 120 kg/m^3 , the northern limit of this band runs along the general line Baltimore-Lexington-Topeka.

3.5.2 – Effects of Material Properties

The effects of ΔH , melting temperature, and thermal conductivity are closely related. ΔH dictates how much energy is available to be transferred from the PCM to the bridge deck; melting temperature determines the temperature at which the bridge deck will be maintained as the ambient temperature drops; and thermal conductivity determines how the bridge deck will react once the energy available from the PCM has been expended.

A ‘larger’ ΔH is always more effective at preventing freeze/thaw cycling, as it represents a ‘larger’ amount of energy that can be used to keep the bridge deck at T_{MELT} . For example, P2 and PT4 both have a melting temperature of 4 °C, but have different values of ΔH : 153 J/g and 195 J/g, respectively². P2 increases service life by at least a year in 35 locations, whereas PT4 increases service life by at least one year in 41 locations.

An optimal range for T_{MELT} exists between roughly 3.55 °C and 6 °C. For example, although HLC has the third highest ΔH , it increased service life by at least one year in only 28 locations, the fewest of any of the PCMs investigated, because it has a very high T_{MELT} (8 °C). At the other end of the scale, despite having the highest ΔH (295 J/g) of any PCM, HPAA increases service life by at least one year in only 32 locations, due to its very low T_{MELT} of 0 °C.

This optimum range of T_{MELT} exists due to the way in which bodies are cooled, which depends heavily on the system’s thermal conductivity. The models show that increasing the thermal conductivity of the composite from 1.5 W/m·K to 3 W/m·K will result in improved performance (i.e. fewer freeze/thaw cycles) *only if* the phase transition temperature of the PCM is within the ‘optimal range’ (Table 6). Outside the optimal range of T_{MELT} , increasing the thermal conductivity will actually increase the number of freeze/thaw cycles that the bridge deck experiences.

Cooling of a hot body (i.e. a bridge deck whose temperature is maintained at T_{MELT} as the ambient temperature drops) will occur primarily due to either convection or conduction. These are similar phenomena whose rates of cooling depend on surface area, a coefficient (either h , the convection heat transfer coefficient, or k_{cond} , the thermal conductivity), and a thermal differential [24]. A greater thermal differential leads to more rapid cooling; a greater thermal conductivity leads to a more rapid transfer of heat from the interior of the body to the surface and even cooling. In systems where the PCM has a high T_{MELT} , the thermal differential is relatively high when the energy from the PCM is expended, leading to rapid cooling. If the thermal conductivity is high, heat from the interior of the body will be rapidly drawn to the surface and dissipated into the environment, meaning that the entire body will cool rapidly (and likely undergo a freeze/thaw cycle). If the thermal conductivity is low, heat cannot flow from the interior to the surface as easily, so although the surface may rapidly cool, the interior of the body will be maintained at a higher temperature and remain undamaged. For bodies incorporating a PCM that has a T_{MELT} in the ‘optimal’ range, the temperature differential is not as great and cooling is thus much slower. A higher thermal conductivity will encourage an even temperature distribution, preventing freezing at the surface.

The concern that reduced thermal conductivity due to PCM incorporation may negatively affect the composite’s effectiveness depends, therefore, on the specific properties of the PCM selected. To refine PCM-concrete composites into practical systems for real-world applications,

² By convention, ΔH is positive for exothermic reactions such as fusion, and negative for endothermic reactions such as melting (although both reactions will occur at T_{MELT}). The values discussed in this paper refer specifically to ΔH_{FUSION} .

increasing the thermal conductivity of the composite (or, for that matter, reducing it, if a PCM with a sub-optimal T_{MELT} is used) is likely to be an important area of inquiry.

3.5.3 – Effects of Weather

Freezing events can vary in how long the event lasts (length) and the minimum temperature reached during the event (depth). The longer the freezing event, the less likely that PCM will be able to keep the temperature of the bridge deck above freezing; the supply of energy from the phase change is not infinite. Deeper freezing events have a similar effect by increasing the temperature differential between the bridge deck and the environment (see Eq. 5), leading to more rapid cooling once that energy is expended.

In the 25 locations with the shortest freezing events, an average of 11.5 of the PCMs increased service life by an average of 4.8 years. In the 25 locations with the longest freezing events, an average of 8 of the PCMs increased service life by an average of 1.2 years. The ‘depth’ of freezing cycles has a less pronounced effect; in the 25 locations with the deepest freezing cycles, an average of 8.2 of the PCMs increased service life by at least one year; in the 25 locations with the least deep freezing cycles an average of 10.9 of the PCMs increase service life by at least one year.

3.5.4 – Effects of User-Defined Damage Level

In the INDOT model, a bridge deck is considered to have reached the end of its service life when some quantifiable property falls below a user-defined damage level (D_S). Barde *et al.* performed calculations using $D_S = 0.6$, however, the exact value of D_S may vary from location to location. Bridge deck service life was therefore calculated using damage levels ranging from $D_S = 0.15$ (least damage) to $D_S = 0.85$ (most damage) for the 175 locations where freeze/thaw damage has a significant impact on service life (Figure 6). Obviously, allowing more damage to occur before replacing the bridge deck will increase the service life of that bridge deck; as D_S increases, the number of locations in which at least one PCM would prove practical increased in a roughly linear fashion. At $D_S = 0.15$, service life was increased by at least one year in an average of 10 ± 4 locations; at $D_S = 0.85$ the average was 48 ± 9 locations. As such, minor variations in the allowed D_S are not likely to have a significant effect on the practicality of the PCM/concrete system.

4 – Conclusions

New technologies that increase infrastructure service life are needed to successfully address the unprecedented maintenance crisis that the world currently faces. These results show that incorporation of PCM in bridge decks is one such technology, which could increase the service lives of bridge decks used by a significant portion of the American population.

Freeze/thaw damage is not a predominant deterioration mechanism in all locations, either because they are too dry or too warm. In the remaining locations, PCM may improve service life by significant amounts in two general areas: the Pacific Northwest and across the southeast. These regions encompass several major metropolitan areas, including Portland, Seattle, Houston, and Atlanta, which *alone* have a combined population of 3.5 million people. A number of generalizations can be made regarding the use of PCM in bridge decks:

- Incorporation of PCM will reduce compressive strength unless preventative measures are taken, either due to the weakness of the incorporation method (LWA, etc.) or retarding behavior displayed by the PCM;

- Increasing ΔH of the PCM or the level of damage that the structure can tolerate, selecting a PCM with a T_{MELT} within the optimal range, and decreasing the length and/or depth of freezing events will all increase effectiveness (i.e. reduce freeze/thaw cycling);
- Increasing the thermal conductivity of the composite will increase effectiveness only if the T_{MELT} of the PCM is within the optimal range. Outside the optimal range, increasing thermal conductivity will actually lower effectiveness; and,
- For PCM incorporation to be proven practical, more work is needed, especially in preventing mechanical property reduction, optimizing composite thermal conductivity, refining the system composition, and understanding long-term behavior.

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TABLES and FIGURES

Component	Mass (g)			
	Control	PT4	PCM 6	PT4-ENC
Type II Cement	1250	1250	1250	1250
Water	437.5	467.5	467.5	437.5
F95 fine sand	659.1	620.9	620.9	659.1
Graded sand (C778)	500.9	432.1	432.1	500.9
20-30 sand (C778)	500.9	355.7	355.7	500.9
S16 coarse sand	975.4	463.4	463.4	975.4
Lightweight Aggregate	-	439.2	439.2	-
Phase Change Material	-	92.0	92.0	-
Encapsulated PCM	-	-	-	108

Table 1 – Mix compositions. ‘ENC’ refers to the mortar containing PCM encapsulated in a polymer pellet.

Phase Change Material	Code	T _{MELT} (°C)	ΔH (J/g)	Locations where effective at D _s =0.6, #
H ₂ O + polyacrylamide	HPAA	0	295	32
91.67 % tetradecane + 8.33 % hexadecane	T/H	1.7	156	29
Tetradecane + docosane	TD	3.55	234	47
Paraffin C14	P2	4	153	35
<i>Proprietary - Vegetable Oil</i>	PT4	4	195	41
Tetradecane + geneicosane	TG	4.55	200	39
Tetrahydrofuran	THF	5	280	48
Paraffin C14	P1	5.5	228	40
<i>Proprietary, Paraffin</i>	PCM6	6	162	33
n-Tetradecane	nT	6	230	39
Formic acid	FA	7.8	247	29
Hydrated lithium chlorate	HLC	8	253	28

Table 2 – PCMs investigated. Italics: commercially available products used in mechanical characterization experiments. All others use data reported in [9].

Variable	Symbol	Units	Value
Concrete Heat Capacity	C	J/(kg·K)	1000
Concrete Thermal Conductivity	k_{cond}	W/(m·K)	1.5, 3
Concrete Density	ρ	kg/m ³	2350
PCM Density in Concrete	ρ_{PCM}	kg/m ³	0, 50, 120
Critical Saturation	S_{CR}	%	0.85
Initial Saturation	S_{INITIAL}	%	0.56
Initial Sorptivity	-	mm/s ^{0.5}	0.002
Sec. Sorptivity	-	mm/s ^{0.5}	0.001
Porosity	V_P	%	0.08
Entrained Air	V_{AIR}	%	0.065
Fitting Factor B	b	mm	5.5
Nick-point Time	t_{nickpt}	Seconds	21600
Deck Depth	D	mm	200
Damage Level	D_S	%	0.6
Fitting Factor A	A	-	12
Change in Sorptivity	ΔS	mm/s ^{0.5}	0.0001

Table 3 – Variables selected for use in CONCTEMP and the INDOT service life model.

Mix	State	k_{cond} (W/m·K)	C_m (J/g·K)
Control	Dry	2.67 ± 0.041	0.62 ± 0.049
	Wet	2.94 ± 0.054	0.74 ± 0.032
PCM6	Dry	1.63 ± 0.005	0.47 ± 0.004
	Wet	2.01 ± 0.053	0.76 ± 0.141
PT4	Dry	1.37 ± 0.008	0.63 ± 0.009
	Wet	1.78 ± 0.018	0.8 ± 0.059
PT4-ENC	Dry	2.47 ± 0.145	0.87 ± 0.106
	Wet	2.68 ± 0.034	1.01 ± 0.056

Table 4 – Thermal conductivity (k) and specific heat by mass (C_m) of mortars in dry and wet conditions. Error values represent standard deviation.

City	State	WBAN Number	ΔLife (years)		City	State	WBAN Number	ΔLife (years)
Bettles	AK	26533	0.9		Oklahoma City	OK	13967	0.6
Annette	AK	25308	0.5		Astoria	OR	94224	2.0
Montgomery	AL	13895	4.4		Salem	OR	24232	1.9
Mobile	AL	13894	7.3		Portland	OR	24229	2.8
Birmingham	AL	13876	1.6		Medford	OR	24225	0.8
Huntsville	AL	03856	0.7		Eugene	OR	24221	0.6
Little Rock	AR	13963	1.2		Pendleton	OR	24155	0.5
Fresno	CA	93193	4.5		Columbia	SC	13883	1.1
Arcata	CA	24283	3.5		Charleston	SC	13880	2.0
Santa Maria	CA	23273	18.8		Lufkin	TX	93987	5.9
Tallahassee	FL	93805	8.6		San Angelo	TX	23034	1.7
Columbus	GA	93842	7.0		Midland/Odessa	TX	23023	1.0
Atlanta	GA	13874	1.6		Wichita Falls	TX	13966	0.8
Athens	GA	13873	1.4		Abilene	TX	13962	1.7
Savannah	GA	03822	1.4		Waco	TX	13959	2.6
Augusta	GA	03820	1.2		Austin	TX	13958	6.1
Macon	GA	03813	3.3		Houston	TX	12960	4.4
Baton Rouge	LA	13970	10.8		San Antonio	TX	12921	8.3
Shreveport	LA	13957	1.4		Fort Worth	TX	03927	0.8
Meridian	MS	13865	2.2		Richmond	VA	13740	0.7
Jackson	MS	03940	1.8		Norfolk	VA	13737	1.1
Cape Hatteras	NC	93729	4.2		Lynchburg	VA	13733	1.3
Charlotte	NC	13881	1.4		Quillayute	WA	94240	2.3
Wilmington	NC	13748	1.6		Seattle	WA	24233	2.4
Raleigh/Durham	NC	13722	0.8		Olympia	WA	24227	1.1

Table 5 – The 50 locations where at least 1 PCM increased service life by at least 1 year. (Note: the increase in service life reported here is an average of all 12 PCMs investigated, therefore, service life increase may be less than 1 year).

PCM (Code)	T _{MELT} (°C)	Locations effective, #		Difference
		k _{cond} = 3 W/m·K	k _{cond} = 1.5 W/m·K	
<i>HPAA</i>	<i>0</i>	<i>29</i>	<i>30</i>	<i>-1</i>
T/H	1.7	45	27	18
TD	3.55	64	45	19
P2	4	41	33	8
PT4	4	49	39	10
TG	4.55	43	37	6
THF	5	54	46	8
<i>P1</i>	<i>5.5</i>	<i>37</i>	<i>38</i>	<i>-1</i>
<i>nT</i>	<i>6</i>	<i>32</i>	<i>37</i>	<i>-5</i>
<i>PCM6</i>	<i>6.1</i>	<i>28</i>	<i>31</i>	<i>-3</i>
<i>FA</i>	<i>7.8</i>	<i>25</i>	<i>27</i>	<i>-2</i>
<i>HLC</i>	<i>8</i>	<i>24</i>	<i>26</i>	<i>-2</i>

Table 6 – Number of locations where the service life of a bridge is predicted to be increased by at least one year with the inclusion of PCM with total composite thermal conductivity (k_{conc}) of 3 W/m·K or 1.5 W/m·K. Table is sorted by increasing T_{MELT}; Locations where increased thermal conductivity decreases the number of effective locations are shown in italics.

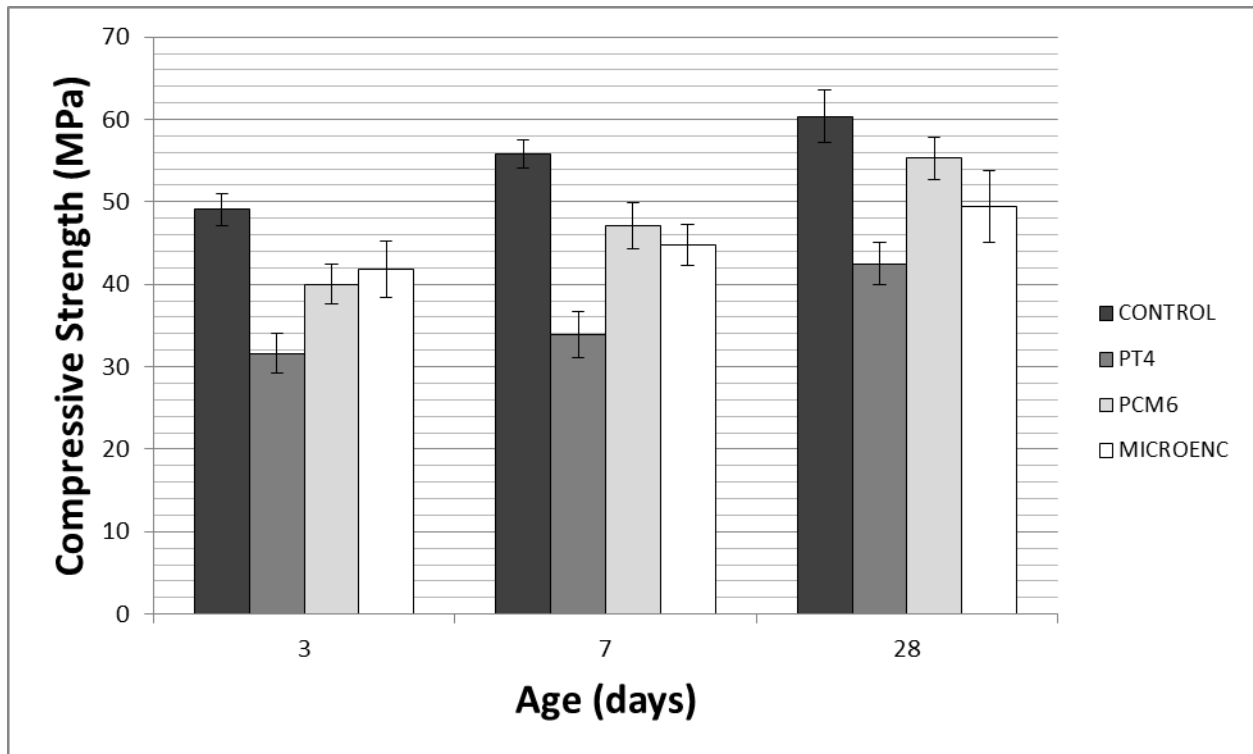


Figure 1 – 3, 7, and 28 day strengths of a control mortar and mortars containing PT4 in LWA, PCM6 in LWA, and encapsulated PT4. Error bars represent one standard deviation.

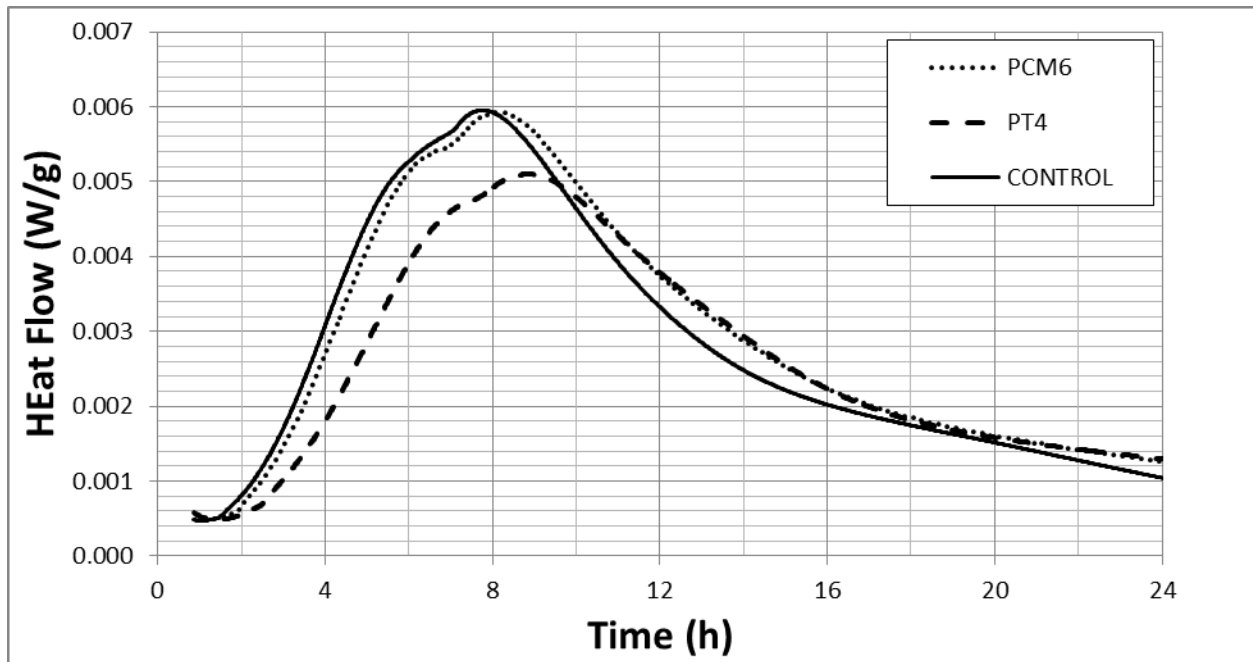


Figure 2 – Heat evolution with time as determined by isothermal calorimetry. Two replicates were tested per mortar and showed minimal variation; one curve is shown.

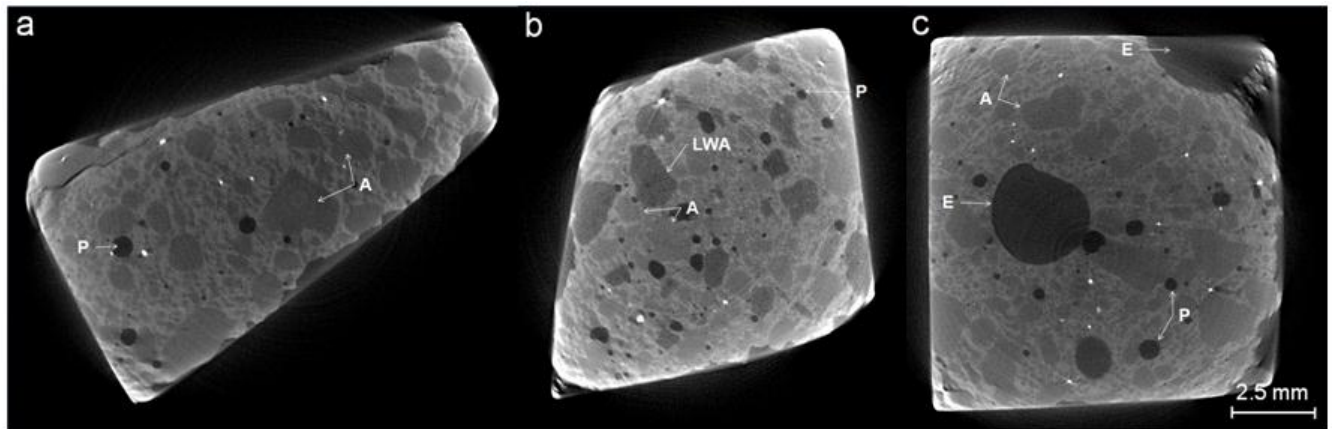


Figure 3 – Microtomographs of investigated mortars. a) Control mortar without PCM, in which quartz aggregate (A) and pores/air voids (P) are easily visible; b) mortar containing LWA-PCM, which appears similar to quartz aggregate, but darker because of its lower density; c) mortar containing encapsulated PCM pellets (E).

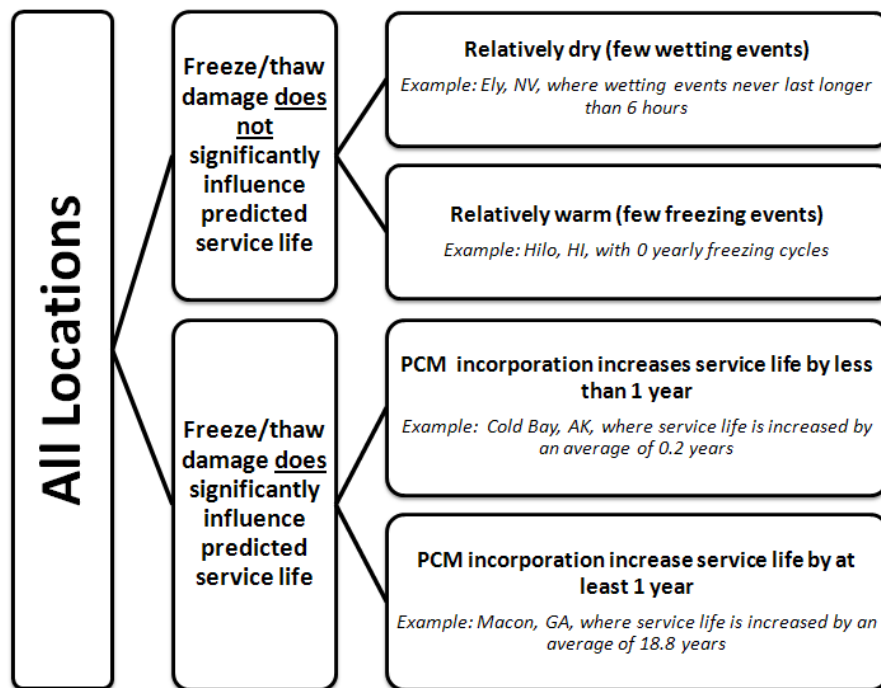


Figure 4 – Breakdown of all locations into 2 groups and 4 subgroups, based on the effect of freeze/thaw damage and the effect of PCM incorporation.

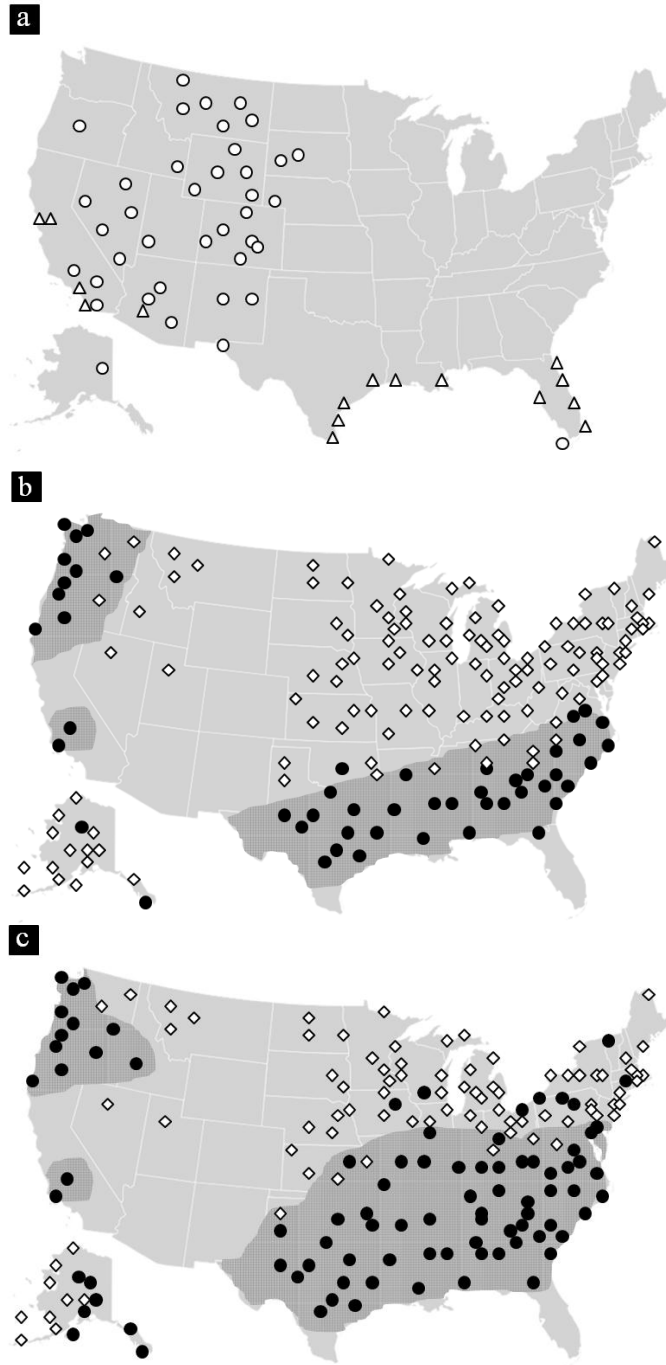


Figure 5 – a) Locations where freeze/thaw damage does not limit bridge deck service life because either $LIFE_{INITIAL}$ (o) or $LIFE_{SECONDARY}$ (Δ) is greater than 20 years. Not shown: all points in Hawaii, Guam, and Puerto Rico. b) Locations where incorporation of 50 kg/m³ of PCM increases bridge deck service life by less than 1 year (◇) or more than 1 year (●). c) Locations where incorporation of the maximum 120 kg/m³ of PCM increases bridge deck service life by less than 1 year (◇) or more than 1 year (●). Shaded areas indicate a rough estimate of the regions where PCM incorporation is practical for extending bridge deck service lives.

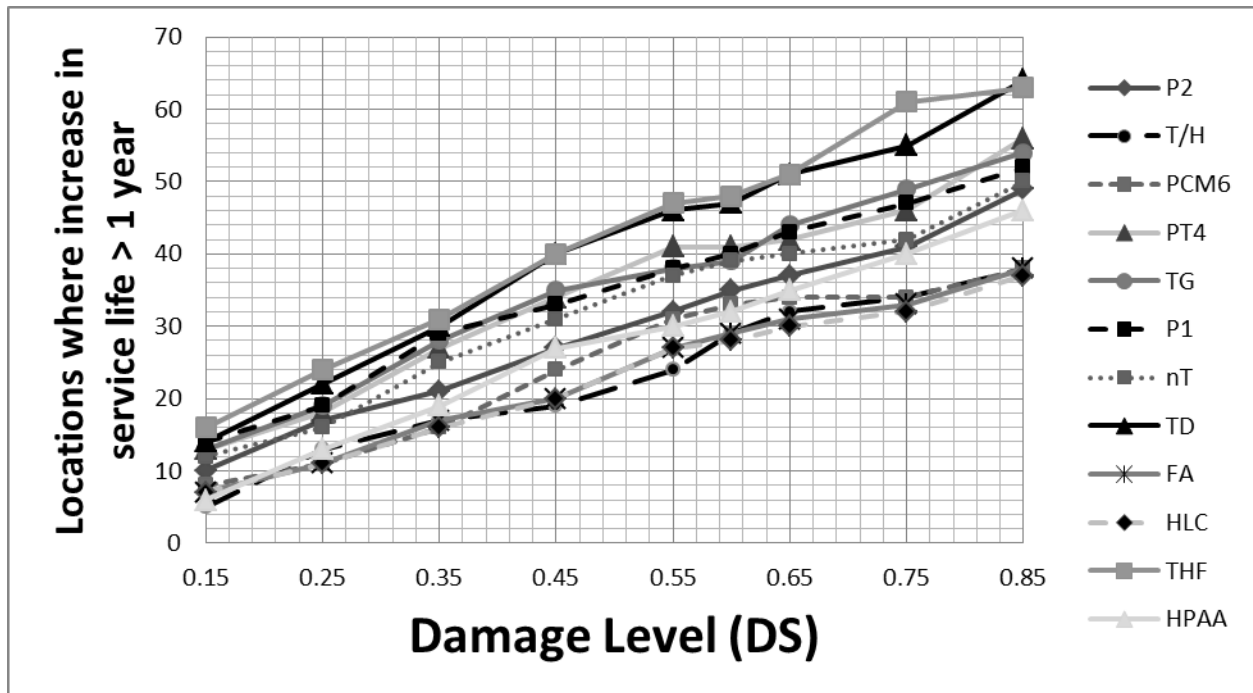


Figure 6 – Number of locations where the incorporation of 2 % PCM increases the service life of a bridge deck by at least 1 year. In the key, PCMs are listed in order of ascending ΔH .

6 – Bibliography

1. Emmons, P.H. and D.J. Sordyl, *The state of the concrete repair industry, and a vision for its future*. Concrete Repair Bulletin, 2006. **July/August 2006**: p. 7-14.
2. ASCE. www.infrastructurereportcard.org. 2010 [cited 2010 June 20, 2010].
3. Officials, A.A.o.S.H.a.T., *Bridging the gap - Restoring and rebuilding the nation's bridges*, J. Horsley, Editor. 2008, American Association of State Highway and Transportation Officials: Washington, D.C.
4. Administration, F.H. *Deficient bridges by state and highway system*. 2011 [cited 2011 25 March 2011]; Available from: <http://www.fhwa.dot.gov/bridge/nbi/defbr10.cfm>.
5. Hong, T. and M. Hastak, *Evaluation and determination of optimal MR&R strategies in concrete bridge decks*. Automation in Construction, 2007. **16**(2): p. 165-175.
6. Lopez-Anido, R., *Life-cycle cost survey of concrete bridge decks- a benchmark for FRP bridge deck replacement*, in *Transportation Research Board 80th Annual Meeting*. 2001, The National Academies: Washington D.C. p. 16.
7. Berg, A.C., et al., *Construction and cost analysis of an FRP reinforced concrete bridge deck*. Construction and Building Materials, 2006. **20**(8): p. 515-526.
8. Kan, L.-L., et al., *Self-healing characterization of engineered cementitious composite materials*. ACI Materials Journal, 2010. **107**(6): p. 617-624.
9. Cabeza, L.F., et al., *Materials used as PCM in thermal energy storage in buildings: A review*. Renewable and Sustainable Energy Reviews, 2011. **15**(3): p. 1675-1695.
10. Pasupathy, A., R. Velraj, and R.V. Seeniraj, *Phase change material-based building architecture for thermal management in residential and commercial establishments*. Renewable and Sustainable Energy Reviews, 2008. **12**(1): p. 39-64.
11. Schossig, P., et al., *Micro-encapsulated phase-change materials integrated into construction materials*. Solar Energy Materials and Solar Cells, 2005. **89**(2-3): p. 297-306.
12. Hunger, M., et al., *The behavior of self-compacting concrete containing micro-encapsulated Phase Change Materials*. Cement and Concrete Composites, 2009. **31**(10): p. 731-743.
13. Kuznik, F., et al., *A review on phase change materials integrated in building walls*. Renewable and Sustainable Energy Reviews, 2011. **15**(1): p. 379-391.
14. Stoll, F., M.L. Drake, and I.O. Salyer, *Use of phase change materials to prevent overnight freezing of bridge decks*, in *IDEA Program*. 1996, Transportation Research Board: Washington, D.C. p. 1-23.
15. Cabeza, L.F., et al., *Use of microencapsulated PCM in concrete walls for energy savings*. Energy and Buildings, 2007. **39**(2): p. 113-119.
16. Bentz, D.P. and R. Turpin, *Potential applications of phase change materials in concrete technology*. Cement and Concrete Composites, 2007. **29**(7): p. 527-532.
17. Bentz, D.P., et al., *Water movement during internal curing: Direct observation using X-ray microtomography*. Concrete International, 2006. **28**(10): p. 39-45.
18. He, Y., *Rapid thermal conductivity measurement with a hot disk sensor: Part 1. Theoretical considerations*. Thermochimica Acta, 2005. **436**(1-2): p. 122-129.
19. Gustafsson, S.E., *Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials*. Review of Scientific Instruments, 1991. **62**(3): p. 797-804.
20. Bentz, D.P., *A computer model to predict the surface temperature and time-of-wetness of concrete pavements and bridge decks*. NISTIR 6551, 2000, National Institute of Standards and Technology: Gaithersburg, MD.

21. Marion, W. and K. Urban, *User's manual for TMY2s typical meteorological years*. 1995, National Renewable Energy Laboratory: Golden, CO.
22. Barde, V., et al., *Relating material properties to exposure conditions for predicting service life in concrete bridge decks in Indiana*, in *Joint Transportation Research Program*, I.O.o.R.a. Development, Editor. 2009, Purdue University: West Lafayette, IN.
23. Martys, N.S. and C.F. Ferraris, *Capillary transport in mortars and concrete*. Cement and Concrete Research, 1997. **27**(5): p. 747-760.
24. Cengel, Y.A. and M.A. Boles, *Thermodynamics: An engineering approach, 4th Edition*. 2002, New York, NY: McGraw-Hill.